New Developments in Design and Application of Long-Throated Flumes

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Abstract

Long-throated flumes provide economical and flexible water measurement capabilities for a wide variety of open-channel flow situations. Primary advantages include minimal headloss, low construction cost, adaptability to a variety of channel types, and ability to measure wide ranges of flows with custom-designed structures. Long-throated flumes can be calibrated using computer programs that apply proven hydraulic theory, thus eliminating the need for laboratory calibration. This paper describes recent advances in the computer software available for design and calibration of long-throated flumes, and highlights two potential flume design issues that have recently come to light. Specifically, there have been field observations of an apparent suction effect below flumes having a vertical drop at the end of the control section; this can lead to significant differences between the actual and theoretical head-discharge rating curve. Second, in flumes that are primarily width-contracted—as opposed to those with a sill that creates a bottom contraction—there is potential for non-modular flow in the throat section when the width to crest length ratio is large, despite the fact that traditional hydraulic theory predicts critical flow. Again, this can cause a significant discrepancy between the actual and theoretical rating curves of a structure.

Introduction

The term *long-throated flume* describes a broad family of critical-flow flumes and broad-crested weirs used to measure open-channel flows. Many specific configurations are possible (fig. 1), depending on the type of approach channel, the shape of the throat section, the location of the gaging station, and the use or lack of a diverging transition section. Bos et al. (1984) described the theory for determining discharge through these flumes. Computer software for rating (Clemmens et al., 1987) and designing flumes (Clemmens et al., 1993) has been well developed in recent years, culminating with the public release of the WinFlume computer program (Wahl and Clemmens, 1998) in late 1999.

Long-throated flumes have particular advantages compared to more traditional devices, such as Parshall flumes. These older devices had to be laboratory-calibrated, because the flow through their control sections is curvilinear. In contrast, the streamlines are essentially parallel in the throat sections of long-throated flumes, making it possible to rate them analytically. Primary advantages of long-throated flumes include:

- Rating table uncertainty of ±2% or better in the computed discharge.
- Choice of throat shapes allows a wide range of discharges to be measured with good precision.
- Minimal head loss needed to maintain critical flow conditions in the throat of the flume.
- Ability to make field modifications and perform computer calibrations using as-built dimensions.
- Economical to construct, and adaptable to a variety of existing canal configurations.

The calculations needed to calibrate, size, and set flumes are iterative, and, as a result, several generations of computer codes have been developed for these purposes, initially by the Agricultural Research Service (ARS) at the U. S. Water Conservation Laboratory in Phoenix, Arizona, USA. In the early 1990's ARS and the International Institute for Land Reclamation and Improvement (ILRI) contracted for the development of an interactive computer program for long-throated flume design. That program (Clemmens et al., 1993), known as FLUME 3.0, operated in an MS-DOS computing environment. Recent advances in computer technology have made that program obsolete.

In 1997 the Bureau of Reclamation (Reclamation) and ARS began cooperative work on an updated version of the flume design software. The new program, WinFlume, is targeted at the Windows 95/NT environments, and also operates under Windows 3.x. WinFlume makes use of the same hydraulic theory used in its predecessors, but has an improved user interface, a new design module, and other new features. WinFlume was programmed in-house by Reclamation to allow for future maintenance and improvement of the software. The program was officially released in late 1999 and can be downloaded by the public from *www.usbr.gov/wrrl/winflume*.

The WinFlume Computer Program

Operation of the WinFlume program is based on an editable graphic display of flume dimensions (fig. 2), auxiliary screens used to enter flume and canal properties and design requirements, and several screens devoted to analysis, review, and output of flume designs. Seven different cross-section shapes are available for the approach and tailwater sections of a flume, and 14 control-section shapes are available, including circular, parabolic, trapezoidal, and complex shapes.

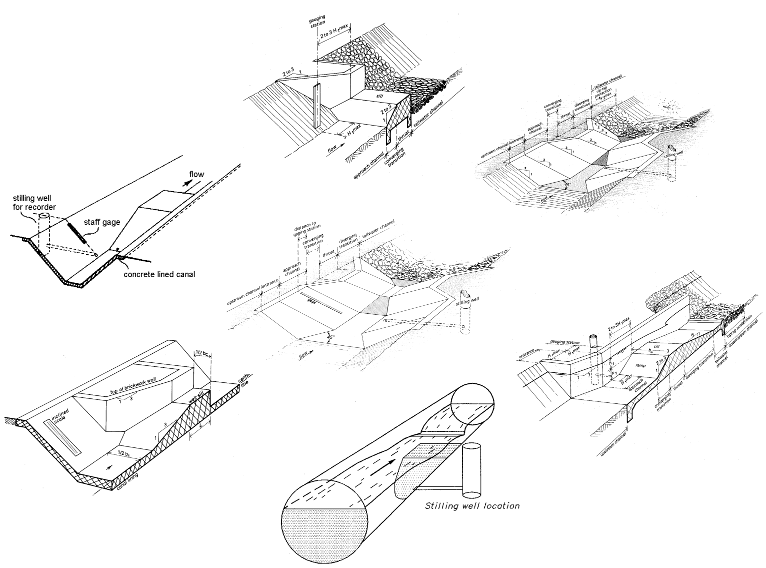

Figure 1. — Long-throated flumes can take many forms.

Basic capabilities of the WinFlume program include: the development of rating tables, rating equations, and related output for existing structures; review of proposed designs against basic design criteria and user-specified design requirements; and assisted development and evaluation of new flume designs. Flume designs developed with WinFlume must satisfy design requirements related to maintaining adequate freeboard and low Froude numbers in the approach channel, ensuring critical flow in the throat section of the structure, and meeting user-specified requirements for flow measurement accuracy (considering the effects of both rating table uncertainty and head-measurement uncertainty).

The WinFlume program supports all features of the previous FLUME 3.0 program, and contains a number of new and improved features. Notable improvements include the Windows-based graphical user interface, improved graphics and printed output, an online help system, a flume wizard to guide users through the data entry process, an improved design module, and integrated printing of full-scale flume wall gages.

Design of Long-Throated Flumes Using WinFlume

The hydraulic design of a long-throated flume using the program is a two step process. First, the throat section must be sized and the sill height determined, and then the lengths of the flume components are refined based on the selected throat geometry so that the structure meets the

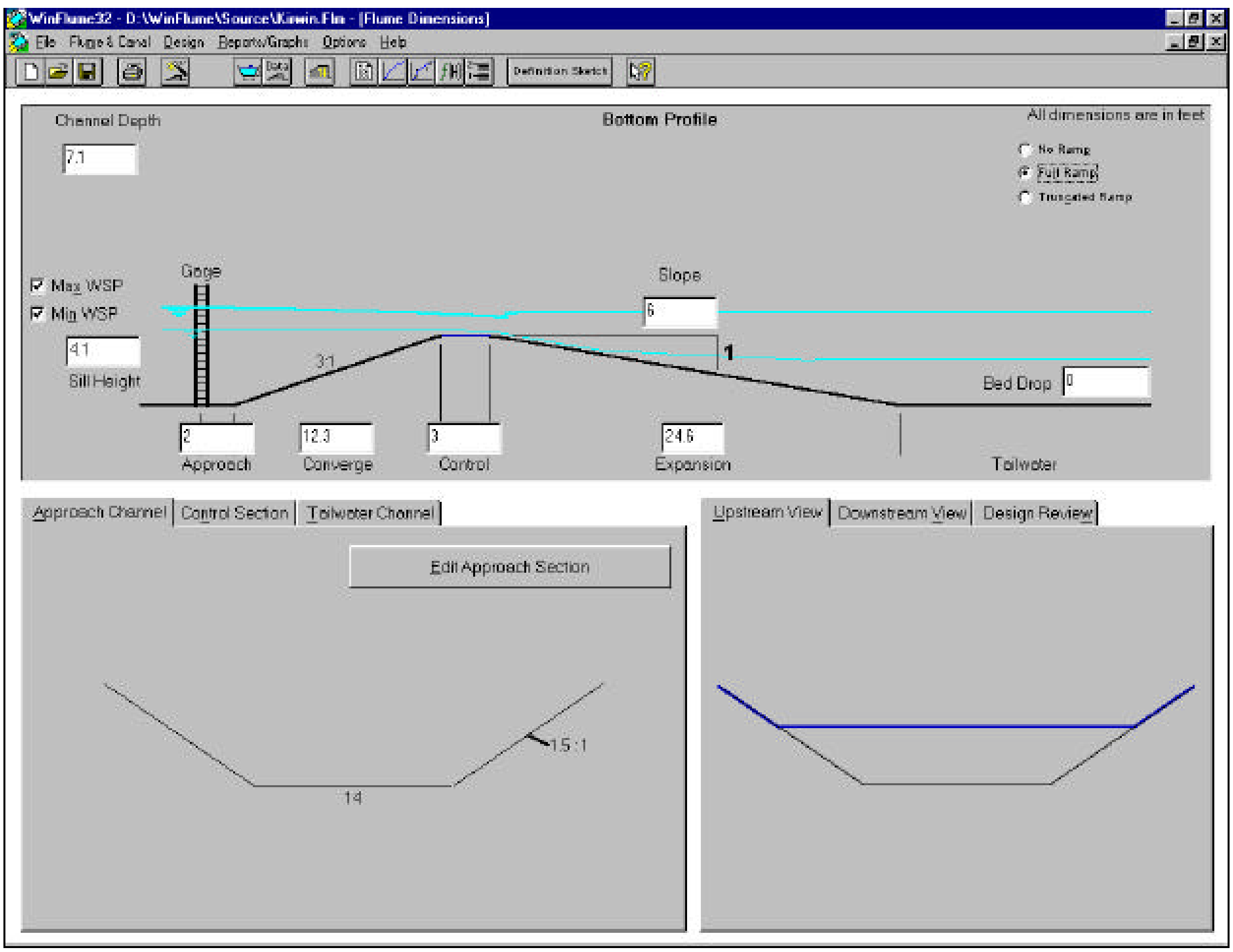

Figure 2. — WinFlume's main screen shows the flume and canal geometry.

requirements of a long-throated flume. The design of the throat must satisfy six design criteria:

- Maintain user-specified freeboard in the approach channel at maximum flow.
- Maintain a Froude number of 0.5 or less in the approach channel at maximum flow.
- Maintain free-flow in the control section at maximum flow.
- Maintain free-flow in the control section at minimum flow.
- Meet user-specified target for flow measurement uncertainty at maximum flow.
- Meet user-specified target for flow measurement uncertainty at minimum flow.

The freeboard requirement is satisfied by reducing the contraction in the throat section shape, while the next three criteria are satisfied by increasing the contraction, either by raising the sill or narrowing the throat section. The flow measurement uncertainty criteria are satisfied by adjusting the throat section width at the base or top of the throat section so that a reasonably large amount of sill-referenced head is generated upstream from the flume. This allows the head to be measured with good relative precision (on a percentage basis), so that the uncertainty in the computed flow rate meets the design objectives.

Design of a flume using WinFlume is a two-step process. First, the throat section is designed, and then the lengths of the flume components (e.g., approach channel, converging transition, throat section, etc.) are adjusted. The throat section can be designed with assistance from WinFlume's design module. The user enters an initial structure definition with a starting throat section shape, dimensions, and sill height. The user also tells the program how to modify the contraction in the throat section. The program then evaluates a complete family of designs derived from the initial structure and presents the user with a list of the acceptable designs, varying from those with the least to the most throat section contraction (and correspondingly the minimum and maximum head loss). From this list, the user can choose a preferred design, with consideration for the advantages and disadvantages of choosing a structure with more or less head loss. Once a preferred design is chosen, refinement of the lengths of flume components and the generation of flume ratings and related output are straightforward procedures.

New Developments in Application of Long-Throated Flumes

Long-throated flumes are a well-developed technology that can be reliably designed and rated using the WinFlume program and other available tools, such as tables of pre-computed flume designs in standard sizes provided in Bos et al. (1984) and the most recent edition of Reclamation's *Water Measurement Manual* (1997). Despite this, the variety of possible designs makes it possible that certain combinations of designs and specific flow conditions may expose limitations of the hydraulic theory used to rate and design flumes. Two specific instances of possible discrepancies between theoretical and observed ratings are described in the remainder of this paper.

Suction Effect in Trapezoidal-Throated Broad-Crested Weirs with Vertical Drop

Trapezoidal-throated broad-crested weirs are commonly used when retrofitting lined trapezoidal canals to add flow measurement capability. The structures are very easy to construct, consisting of just a horizontal sill and an approach ramp; the existing canal serves as the approach channel and forms the side walls of the throat section. Unless a structure with minimal head loss is required, these weirs are usually constructed with a vertical drop at the downstream end of the throat section to minimize the length and cost of the structure.

There have been scattered reports in recent years of discrepancies between flows measured by these weirs and corresponding current-meter discharge measurements, when the structures are operating with a low tailwater level. Reported differences have been on the order of 6% at high flows, with the weirs registering lower flow rates than the current-meter discharge measurements (i.e., the weirs apparently pass more flow for a given head than is indicated by the computed rating curve). The problem has only been reported on weirs constructed with only a bottom contraction and with side walls that are continuous over the length of the structure so that the nappe is in contact with the side walls and natural aeration is prevented.

The presumed mechanism causing the difference is a suction effect at the downstream end of the control section that increases the flow over the weir for a given upstream head. This is similar to the error that occurs when a rectangular suppressed sharp-crested weir is not properly ventilated, causing adherence of the nappe to the downstream side of the weir plate. In the broad-crested weir structure, the nappe is adhering to the face of the vertical drop at the downstream end of the crest when the tailwater is low. When the tailwater is high, the suction seems to be reduced or eliminated, perhaps by the presence of a turbulent reverse roller at the base of the weir or a skimming flow and separation from the downstream face of the weir at the highest tailwater levels (i.e., approaching the modular limit).

Measures to address this problem in the field could include the addition of ventilation pipes or the placement of cinder blocks or other obstructions downstream of the weir to disrupt the flow and allow aeration of the underside of the nappe as it exits the throat section (personal communication, Stuart Stiles, Utah State University). It may be more appropriate to add at least a short length of sloping downstream ramp to the structure. A 6:1 slope and a length at least three times the upstream sill referenced head are recommended. Such downstream ramps are commonly used to reduce the total head loss required to maintain critical (modular) flow through the structure.

The ARS is presently conducting tests at the U.S. Water Conservation Laboratory of a 1/6-scale model of a broad-crested weir experiencing this problem at the Elder Canal Heading on the Imperial Irrigation District, California. Depending on the results of the laboratory testing, the WinFlume program may be modified in the future to identify designs with a potential for the suction effect and suggest the addition of a downstream ramp.

Limits on the Length-to-Width Ratio of the Throat of Width-Contracted Flumes

Critical flow is produced in the throat section of a long-throated flume due to vertical and/or horizontal contraction of the flow as it passes from the approach channel into the throat section. The hydraulic theory for determining the amount of contraction required to produce critical depth accounts for the effects of width vs. depth contraction at the critical section through the use of the hydraulic depth parameter in the Froude number, $\mathrm{Fr}=V/(gD)^{0.5}$, and other critical-depth relations. The hydraulic depth, D, is the flow cross-sectional area, A, divided by the top width of the section, T. Critical-depth flow relations do not consider the actual mechanics of the flow in the transition section connecting the approach channel to the throat section. The width contraction and depth contraction are both assumed to affect the flow uniformly throughout the cross section. Thus, the depths and velocities at the approach channel and at the critical section are also assumed to be uniform across the width of each section. In some special situations, this assumption appears to be invalid.

Parshall flumes are in wide use throughout the world for irrigation water measurement, but at many sites they have fallen into disrepair and are no longer accurate measurement devices. Some such structures offer promise for rehabilitation through conversion to long-throated flumes. This conversion can take place in a number of ways, but one possibility is to simply fill the sloped floor of the throat section and expanding transition with concrete to create a fully width-contracted device with a level floor through the end of the throat section, and slight downstream ramp in the diverging transition (see fig. 3). Laboratory testing by the ARS's U.S. Water Conservation Laboratory in Phoenix, AZ of such a modification of a 1-ft (0.30-m) Parshall flume proved successful, with the rating of the modified flume matching the rating computed by the WinFlume program. However, when an attempt was made to extend this conversion method to an 8-ft (2.44-m) Parshall flume, which was tested in the ARS laboratory in a ¼-scale model, differences of 7 to more than 30 percent were observed between the actual and theoretical discharge of the structures (fig. 4). Visual observations of the flow suggested that the problem was caused by the fact that the throat length of the converted structure was too short to allow the side contraction to be felt at the centerline of what should have been the critical section. Standing waves that were generated on the surface of the flow at the entrance to the throat section could not propagate to the centerline of the throat before the flow reached the end of the throat section. When a small raised sill was added to the model, the preliminary laboratory rating of the structure with the sill matched the rating predicted by WinFlume (with a sill). It is important to note that the throat sections of the prototype 1-ft and 8-ft Parshall flumes (and all intermediate sizes) are 2 ft (0.61 m) long. Parshall flumes of different sizes are

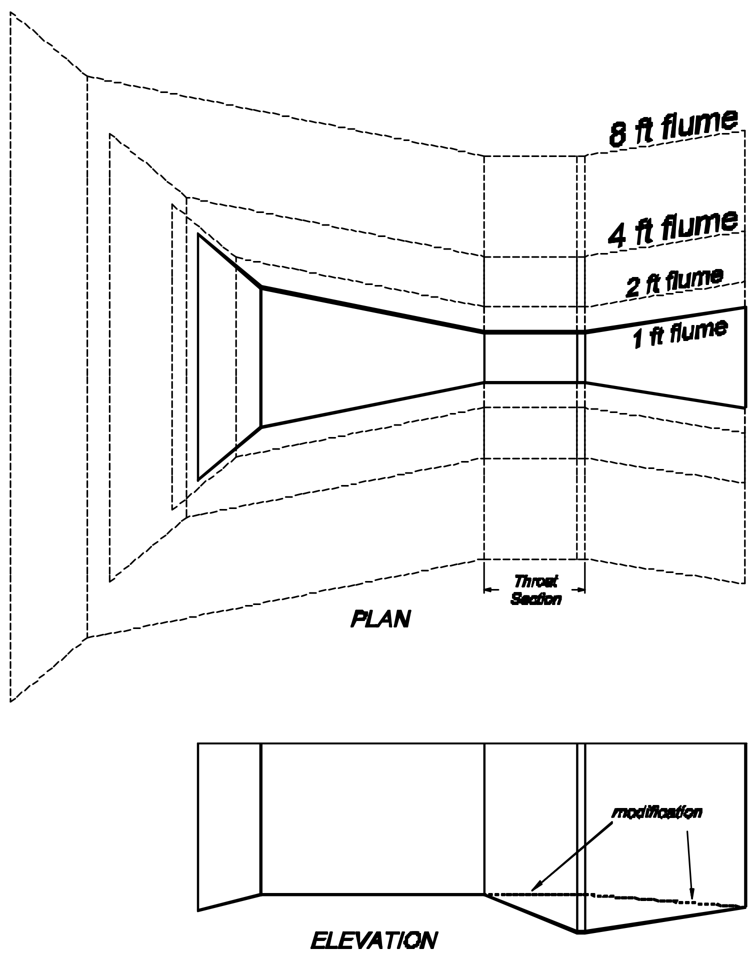

Figure 3. — Details of 1, 2, 4, and 8 ft (0.30, 0.61, 1.22, and 2.44 m) wide Parshall flumes. The elevation view shows the 1-ft flume and the proposed modification of the throat section for converting these structures to long-throated flumes. Note in the plan view the different length-to-width ratios of the throat in each flume.

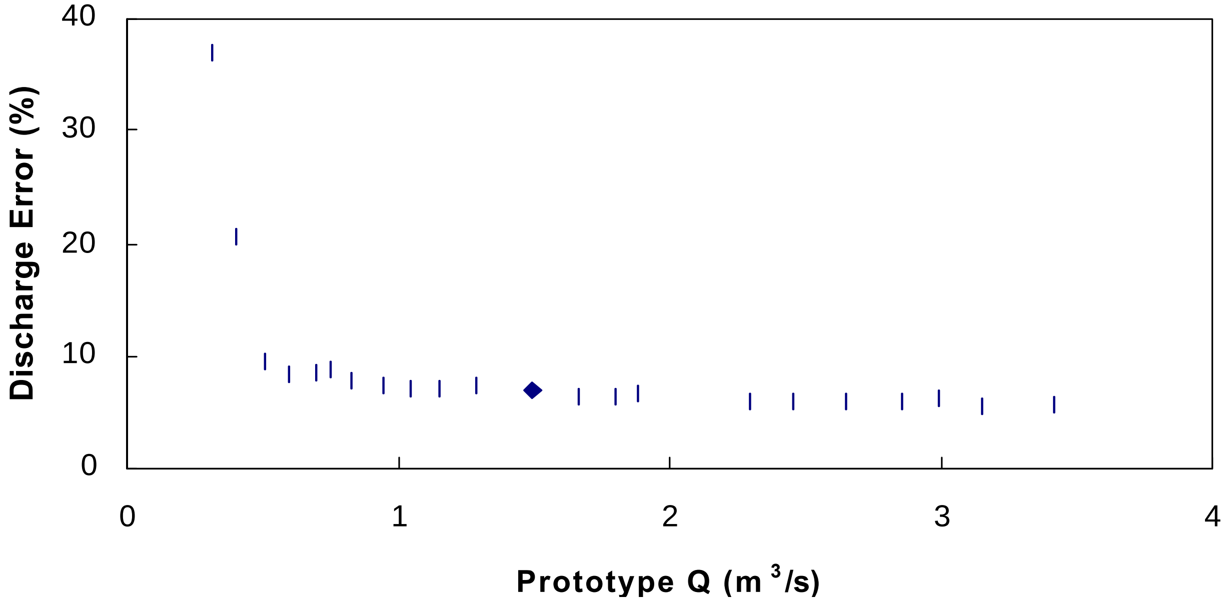

Figure 4. — Discharge errors (reductions) from the theoretical rating for a 2.44-m (8-ft) wide Parshall flume converted to a width-contracted long-throated flume as shown in figure 4. These data were collected from a 1/4-scale model.

not scale models of one another. Thus, the width-to-length ratios of the 1-ft and 8-ft flumes were 1:2 and 4:1, respectively, a dramatic difference.

Critical depth is generally assumed to occur in a long-throated flume at a distance about two-thirds of the crest length downstream from the upstream edge of the throat. At this cross-section the Froude number is unity, and since the Froude number expresses the ratios of the flow velocity and the celerity of a shallow-water wave, any disturbance of the flow at a section with a Froude number of 1 will propagate across the channel and downstream at a 45° angle to the flow direction, and cannot propagate upstream. At other Froude numbers, the disturbance will propagate across the channel at an angle $\theta = \tan^{-1}(Fr)$ away from the flow direction.

If we consider a throat section with length L and width w, and assume that the flow throughout the throat section has a Froude number of 1, then a crest length of $L = 0.75w$ would be required to allow a disturbance to propagate from the side wall to the centerline of the channel within a flow distance of $2L/3$. If we only require the disturbance to reach the centerline before reaching the downstream end of the throat, then a crest length of $L=0.5w$ would be acceptable. In practice, the disturbance may need to propagate farther than the channel centerline for critical flow to be reliably produced across the full width of the section, which would require additional crest length. On the other hand, the Froude number upstream of the critical section will be less than 1.0, so the propagation angle of the disturbance created by a side contraction will be greater than 45° from the flow direction at the entrance to the throat (i.e., the disturbance will cross more nearly perpendicular to the flow direction), and will tend toward 45° as the flow approaches the critical section. The relative importance of these factors and how they affect the required crest length is unknown at this time.

In an attempt to determine the limiting conditions for producing a successful width-contracted long-throated flume, the Bureau of Reclamation used the computational fluid dynamics (CFD) model FLOW-3D to investigate 4-ft (1.22-m), and 2-ft (0.61-m) Parshall flumes that were converted to long-throated flumes in the manner already described. The FLOW-3D® model by Flow Science is a finite difference, free surface, transient flow modeling system based on the Navier-Stokes equations, using up to three spatial dimensions. The finite difference equations are based on a fixed Eulerian mesh of non-uniform rectangular control volumes defined in an orthogonal coordinate system as opposed to a body-fitted system. Free surfaces and material interfaces are defined by a fractional volume-of-fluid function. The model was used to simulate a range of flow rates through the structures to develop head-discharge rating curves that could be compared to the rating curves produced by WinFlume. FLOW-3D was also used to model the performance of an unmodified Parshall flume to verify its ability to perform this kind of simulation. The model was able to reproduce the published rating curve for a standard 8-ft Parshall flume with errors of less than ±2%.

Figure 5 shows results from the CFD simulations. Data are shown for both flume sizes in tests where the tailwater level below the modeled flume was set well below the level that might affect flow in the throat section of the structure. Data are also shown for the 4-ft flume in a series of tests where the tailwater level was set at approximately the modular limit of the structure, as computed using WinFlume. Simulations were primarily run in the lower range of heads for these structures (less than 0.35 m), since the results indicated that percentage differences between the theoretical and simulated ratings increased with decreasing head.

The upper plot shows that the discharge is lower than that predicted by the WinFlume model for essentially all cases. This is consistent with the hypothesis that critical depth is not occurring in the throat section, since, by definition, when critical depth occurs we obtain the theoretically maximum possible flow rate for a given upstream head.

The lower plot in figure 5 shows percentage errors for each series of tests. The tests on the 4-ft flume with high tailwater show that raising the tailwater does increase the error. Again, this indicates that there is a portion of the throat section in which critical depth does not occur, allowing hydraulic communication from the downstream to the upstream side of the structure through at least a part of the throat section. As a result, tailwater levels can affect the upstream head and increase the measurement error.

The FLOW-3D tests showed that the magnitude of the flow measurement errors was reduced in the 2-ft flume compared to the 4-ft flume, but was still significant at all flow rates tested. The percentage errors at higher heads are similar in magnitude to those observed in the ¼-scale model of the converted 8-ft flume, and are also reduced in the 2-ft flume as compared to the 4-ft flume.

Thus far, only the 1-ft (0.30-m) Parshall flume tested by ARS (L/w=2) has performed satisfactorily after being converted to a solely width-contracted long-throated flume. CFD simulations of similar flumes with L/w ratios of 1 and 0.5, and laboratory testing of a flume with L/w=0.25 have demonstrated that there are increasing errors in measured discharge as L/w is reduced. Further testing is needed to determine the necessary L/w ratio for a width-contracted flume so that this can be added as a design criterion in the WinFlume program. Research is also needed to determine the necessary L/w ratio for producing uniform critical depth flow in flumes that have partial width and floor contractions, especially when the floor contraction is relatively slight.

Conclusions

Long-throated flumes are a well-developed technology that provides economical and flexible water measurement capabilities for a wide variety of open-channel flow situations. The structures have low head loss requirements among other advantages, and can be calibrated using a state-of-the-art computer program available to the public on the Internet. Two particular flume configurations are the subject of ongoing research to evaluate potential operational problems and establish limits on the range of application of the hydraulic theory used to rate long-throated flumes and ensure the occurrence of critical flow in the throat section. At this time, for flumes that are primarily width-contracted, the authors recommend maintaining a crest length-to-width ratio of 2:1 or greater in the throat section. For flumes with a vertical drop at the end of the throat section, it may be necessary to add a downstream ramp or other nappe-disrupting feature to prevent a suction effect at low tailwater conditions that may affect the rating of the structure.

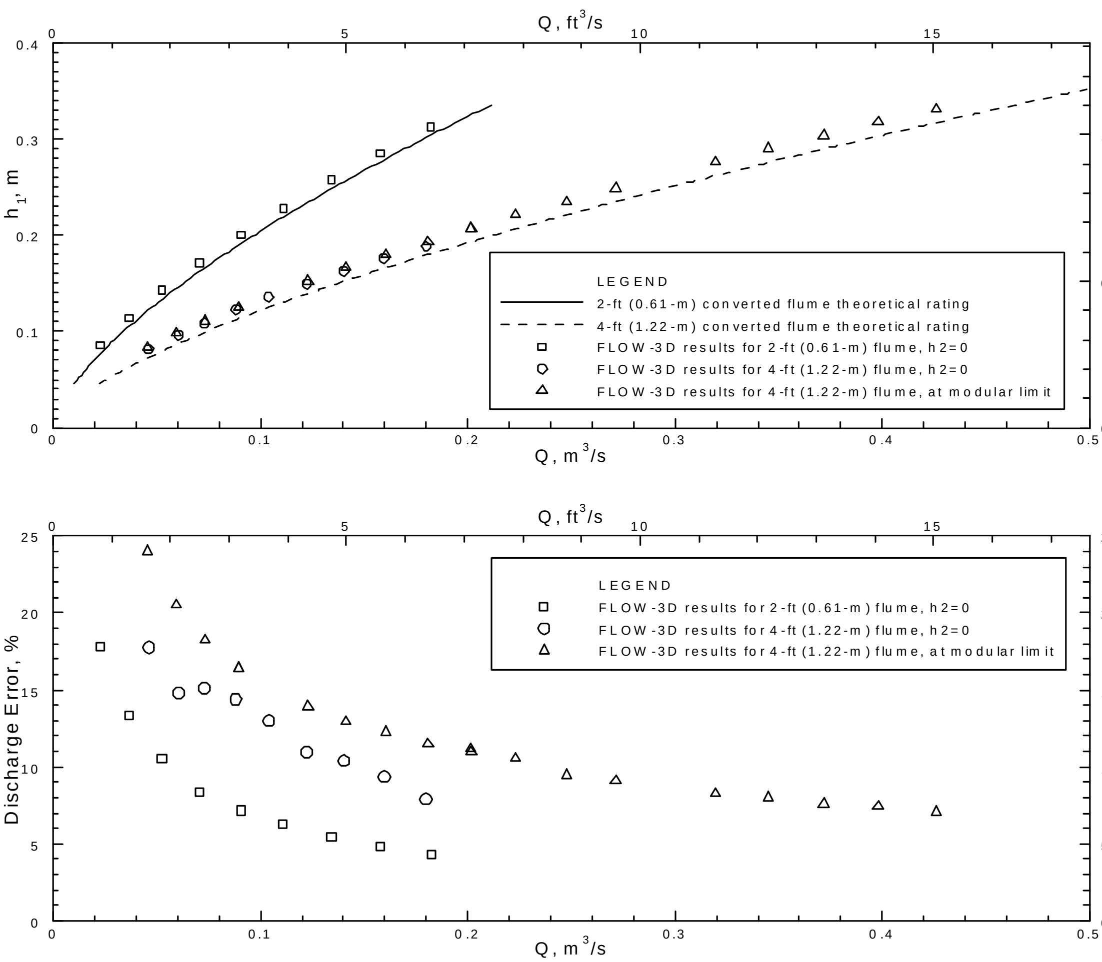

Figure 5. — Comparisons of theoretical rating curves developed using the WinFlume program and results of CFD simulations of 2 ft (0.61 m) and 4 ft (1.22 m) wide Parshall flumes converted to width-contracted long-throated flumes (upper plot). The lower plot shows the percentage errors in discharge measurement.

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